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OPTICALLY DIGITAL COMMUNICATION AND PROCESSING AT THE QUANTUM LIMIT

Northwestern University

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APPROVED: Robert Kaminski

ROBERT L. KAMINSKI
Project Engineer

FOR THE DIRECTOR:

WARREN H. DEBANY, JR., Technical Advisor
Information Grid Division
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OPTICALLY DIGITAL COMMUNICATION AND PROCESSING AT THE QUANTUM LIMIT

Prem Kumar
Horace Yuen

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Principal Investigator: Prem Kumar
Phone: (847) 491-4128
AFRL Project Engineer: Robert L. Kaminski
Phone: (315) 330-1865

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Prem Kumar and Horace Yuen

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Northwestern University
Department of Electrical and Computer Engineering
2145 N. Sheridan Road
Evanston IL 60208-3118

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13. ABSTRACT *(Maximum 200 words)*

A theoretical/experimental research program was undertaken to settle the fundamental limits of all-optical regeneration, switching, and time recovery, with the aim of quantifying the optimal performance and evaluating how low the signal can be tolerated before amplification/regeneration is necessary. Towards this goal the contractor performed a quantum-mechanical analysis of a nonlinear interferometer that achieves optical switching via cross-phase modulation resulting from the Kerr effect. Northwestern showed how this device performs as a very precise optical regenerator, highly improving the transmitted bit-error rate in the presence of loss. On the experimental side, they made progress on an ongoing experiment to measure the quantum noise properties of a nonlinear-fiber Sagnac interferometer. A dual polarization scheme was devised to suppress the guided acoustic-wave Brillouin scattering in the fiber that hampers measurement of the quantum noise. Initial test showed good suppression of the classical noise resulting from guided acoustic-wave Brillouin scattering.

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1 Introduction

The high demand likely to be placed on the capacity of telecommunication networks in the near future—especially in view of redefining mass media by computer-based systems—urges conversion of hybrid electro-optical signal processing to all-optical processing, exploiting the largest bandwidth available in the optical domain. One way of catering to this demand is through multiplexing in the time as well wavelength domains. Using picosecond-duration optical pulses, which could take the form of solitons over portions of the network, one can achieve multiplexing first in the time domain (TDM) for local to metropolitan-area network applications and then in the wavelength domain (WDM) for wide area coverage. These networks, in metropolitan and wide-area applications, will be required to carry information over distances of hundreds to thousands of kilometers. In such communication networks, signal splitting at various nodes (for example, for destination processing and add/drop multiplexing) and the unavoidable transmission losses along the interconnecting optical-fiber spans set the crucial limitation on the maximum network size. In addition, the optical amplifiers used to boost the signals, along with the losses, introduce noise of quantum mechanical origin, which manifests itself either as signal (photon number) fluctuations, or in the form of timing errors (Gordon-Haus jitter), placing the ultimate limits on the network capacity.

The above scenario leads one to conclude that the key issue to be addressed is how to take advantage of the powerful digital-processing techniques in the pure-optical domain, that minimize the detrimental effects of noise at the very fundamental quantum level. The idea is that, for digitally encoded data [1's (0's) represented by the presence (absence) of pulses], instead of using linear amplifiers—which act on signals in an *analog* fashion and inevitably introduce 3dB of noise—one can employ *digital-switching amplifiers* or *optical regenerators.* At the same time, pure-optical digital-switching is potentially much more reliable and faster than electro-optical switching. Furthermore, optical switching will also be needed to implement other networking functions, such as demultiplexing to process at very high speed the header of a data packet used for addressing it to different users on the network.

A very promising method for achieving optical switching is based on *optical nonlinear loop mirrors*, essentially Sagnac interferometers with self- or cross-phase modulating Kerr

medium. Experimental studies at high (semiclassical) power levels have shown that this method achieves very accurate optical switching, with the possibility of *shepherding* soliton streams [1]. Also, recently, all-optical self-synchronization for high-speed photonic networks [2], self-routing with address recognition [3], and regeneration up to 40 Gb/s has been practically demonstrated [5].

At Northwestern our focus has been to use such nonlinear-fiber loop mirrors as phase-sensitive amplifiers. We have recently demonstrated the use of such an amplifier in the storage of picosecond optical pulses in a fiber storage buffer [6, 7]. Optical storage buffers are an essential component of high-speed TDM optical networks [8]. They can be used for queuing packets while transmitters await access to the network, for enabling receivers to handle data at rates faster than can be processed, and for rate-conversion in conjunction with optical switches.

The questions now are: what are the performance limits when optical switching is operated at the quantum limit throughout the network; both for amplification (i.e., regeneration) and multiplexing/demultiplexing? To what extent can the degradation due to quantum fluctuations be optically restored, and how accurate is the timing stabilization?

2 Research Performed

With the above motivations in mind, and also because the quantum loop mirror is very promising as a multiple-purpose device (for switching, amplification, demultiplexing, retiming, self-synchronization or clock-recovering, optical AND gates, etc.), our proposal was to perform an extensive analysis of this device in the quantum regime, both experimentally and theoretically.

Goal: Set up a quantum model of a Sagnac switch and evaluate bit-error rates for a regenerator line.

Accomplishments: We performed a quantum-mechanical analysis of a nonlinear interferometer that achieves optical switching via cross-phase modulation resulting from the Kerr effect. We showed how it performs as a very precise optical regenerator, highly improving the transmitted bit-error rate in the presence of loss. (see Figs. 2 and 3). A log-log plot of the

BER B resulting from our analysis versus N, the number of regenerators along the line, is reported in Fig. 4 for different magnitudes of the input coherent-state signal amplitude β. As shown, the BER increases fast for the first ten-twenty regenerators and then there is a transition to a very stable linear regime $B = C(\beta)N$, with $C(\beta) = 10^{-0.44\pm0.02-(0.0356\pm0.0001)|\beta|^2}$. So, for example, after $N = 10^2$ optical repeaters and for input amplitude $\beta = 20$, corresponding to 400 photons, the BER is $B = 2 \times 10^{-13}$.

A paper describing the results of our analysis was published in the IEEE Photonics Technology Letters. See G. M. D'Ariano and P. Kumar, "A quantum-mechanical study of optical regenerators based on nonlinear-loop mirrors," *IEEE Photonics Technology Letters*, Vol. 10, No. 5, 1998, pp. 699–701.

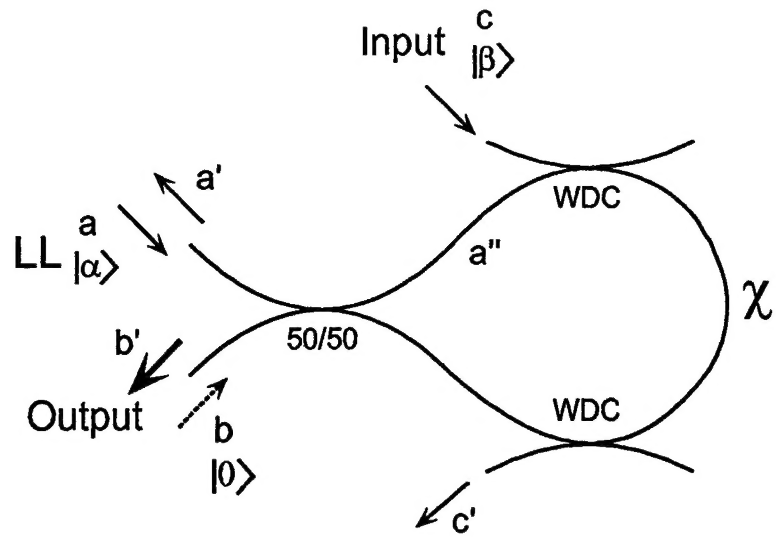
Goal: Measure quantum properties of a nonlinear-fiber Sagnac switch.

Accomplishments: Progress was made on an ongoing experiment to measure the quantum noise properties of a nonlinear-fiber Sagnac interferometer. A dual polarization scheme was devised to suppress the guided acoustic-wave Brillouin scattering that hampers measurement of the quantum noise. Initial tests showed good suppression of the classical noise resulting from guided acoustic-wave Brillouin scattering. These experiments are being continued with support from other sources of funding.

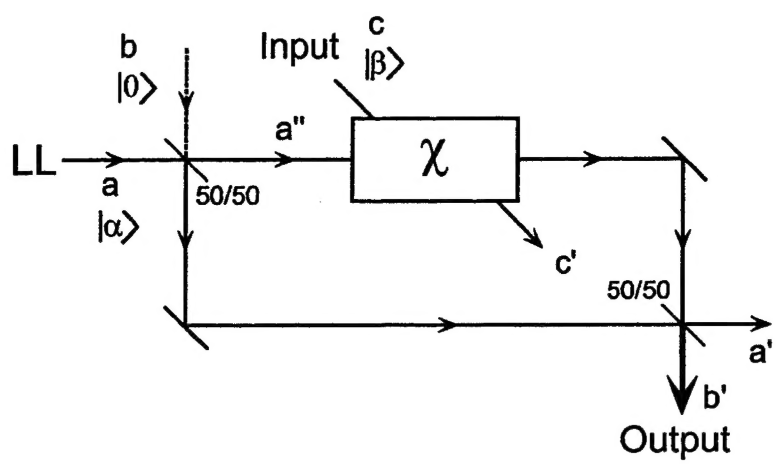
Below we describe in some detail the results obtained during the period of this grant.

2.1 Performance of a Regenerator Line Based on the Sagnac Switch

A fiber-optic nonlinear Sagnac interferometer is depicted in Fig. 1 along with its equivalent Mach-Zehnder interferometer. The input mode $\hat{a}$, assumed to be in a coherent state $|\alpha\rangle$, is split into the two arms of the interferometer by a 50/50 beam splitter. In one arm the pertaining field mode $\hat{a}''$ undergoes a Kerr nonlinear phase shift $\hat{U} = \exp[i\chi\hat{a}''^{\dagger}\hat{a}''\hat{c}^{\dagger}\hat{c}]$ that depends on the state of the other input mode $\hat{c}$ of a different frequency and/or polarization. Here, by the hooded letters $\hat{a}, \hat{b}, \hat{c}$ we are denoting the annihilation operators of the respective field modes, by their daggered letters we mean the respective creation operators, and χ denotes the overall Kerr coupling, i.e., the third-order susceptibility of the medium integrated over its length along the direction of propagation. For $\hat{c}$ in the vacuum state there is no



(a)



(b)

Figure 1: Schematic of a nonlinear fiber-optic Sagnac interferometer (a), and its Mach-Zehnder equivalent (b). WDC, wave-length dependent coupler.

nonlinear phase shift for $\hat{a}''$, and for an appropriate choice of phases in the two arms of the interferometer the field modes exactly recombine at the second 50/50 beam splitter, so that the input coherent state $|\alpha\rangle$ emerges as the state for the output mode $\hat{a}'$. If $\hat{c}$ is non-vacuum, then a Kerr phase shift of magnitude π would make the state $|\alpha\rangle$ switch toward the output $\hat{b}'$. Strictly speaking, a perfect π phase shift is achieved only with $\hat{c}$ in a number state $|n\rangle$, with $n\chi = \pi$. However, as we will see in the following, the interferometer switches effectively even in the presence of Poissonian intensity fluctuations, i.e., when $\hat{c}$ is in a coherent state, say $|\beta\rangle$, with $|\beta|^2\chi = \pi$. The Sagnac interferometer in Fig. 1, when used as a repeater, is regarded as having the input at port c and the output at port b'. When the coherent state $|\beta\rangle$ corresponding to bit *one* enters port c the interferometer approximately re-transmits the strong coherent state $|\alpha\rangle$ of the local-laser (LL) mode $\hat{a}$; otherwise, it just re-transmits the vacuum state corresponding to bit *zero*.

The relation between the input state $\hat{\rho}_{\text{in}}$ at $\hat{c}$ and the output state $\hat{\rho}_{\text{out}}$ at $\hat{b}'$ of the Sagnac repeater is easily derived; it is given by the following map:

$$\begin{aligned} \hat{\rho}_{\text{out}} &= \Gamma_{\chi,\alpha}(\hat{\rho}_{\text{in}}) \\ &\equiv \sum_{n=0}^{\infty} \left|\alpha e^{\frac{i}{2}n\chi} \sin(n\chi/2)\right\rangle \langle n|\hat{\rho}_{\text{in}}|n\rangle \left\langle \alpha e^{\frac{i}{2}n\chi} \sin(n\chi/2)\right| , \end{aligned} \tag{1}$$

which shows that the resulting output state is a mixture of coherent states. When the input is in a high mean-intensity coherent state $\hat{\rho}_{\text{in}} = |\beta\rangle\langle\beta|$ with $|\beta|^2 = \pi/\chi \gg 1$, then the output state in Eq. (1) is approximated by the dephased coherent state

$$\hat{\rho}_{\text{out}} \simeq \int_{-\infty}^{+\infty} \frac{d\varphi}{\sqrt{2\pi\Delta^2}} e^{-\frac{\varphi^2}{2\Delta^2}} \left|i\alpha e^{i\varphi}\cos\varphi\right\rangle \left\langle i\alpha e^{i\varphi}\cos\varphi\right|, \tag{2}$$

having a small variance $\Delta^2 = \pi^2/(4|\beta|^2) = \pi\chi/4 \ll 1$. The state in Eq. (2) has a banana-shaped Wigner function, corresponding to a quasi-Poissonian photon-number distribution with $\langle \hat{b}^\dagger \hat{b}\rangle \simeq |\alpha|^2 \exp(-\Delta^2)$ and a Gaussian phase distribution with $\langle \Delta\phi^2\rangle = |\alpha|^{-2} + \Delta^2$.

We now consider an on-off communication scheme implemented on a lossy line with transmitted average power $P = |\gamma|^2/2$, and the *zero* and the *one* bit represented by the vacuum state $|0\rangle$ and the coherent state $|\gamma\rangle$, respectively. After a loss $1-\eta$ we insert a repeater with its Kerr coupling tuned to the switching value $\chi = \pi/(\eta|\gamma|^2)$ and the LL amplitude set to $\alpha = -i\gamma$, such that the original amplitude γ is approximately re-established at the output [for the $-i$ phase factor see Eq. (2)]. After a further loss $1-\eta$ another repeater

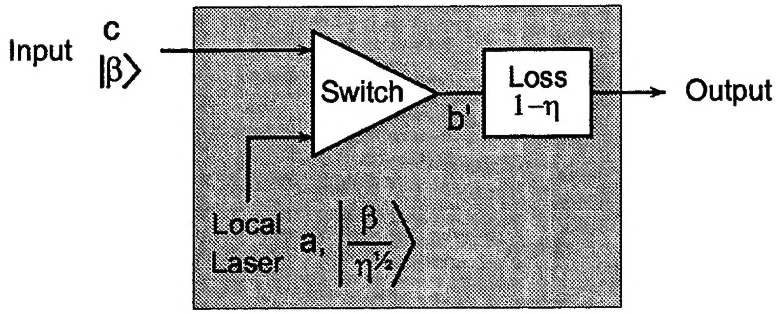


Figure 2: Schematic representation of the nonlinear Sagnac interferometer used as a regenerator along a transmission line. Considering only the relevant ports, the regenerator is a three-port device. The optimal working point for the local laser is shown, which depends on the loss following the regenerator.

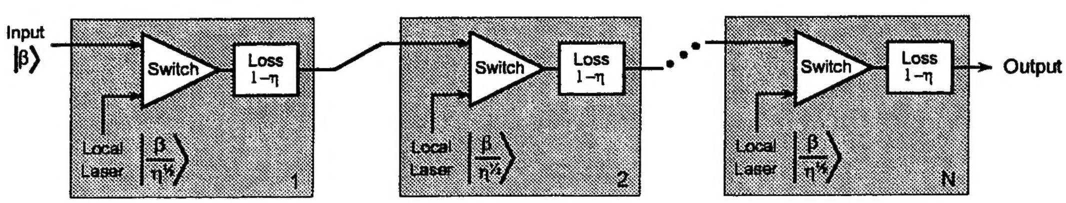


Figure 3: Schematic of a lossy line with distributed optical regenerators.

is inserted, and so forth, for an overall N number of steps (see Figs. 2 and 3). Since the only effect of loss on coherent states is just an amplitude rescaling by the factor $\sqrt{\eta}$, and because the output state from the Sagnac interferometer is a mixture of coherent states, it turns out that the overall state transformation for a loss $1-\eta$ preceded by a repeater depends only on the signal level β at the repeater input, independently of η, as long as the LL is set at the loss-compensating amplitude value $-i\eta^{-1/2}\beta \equiv -i\gamma$ and the Kerr coupling is tuned to the switching value $\chi = \pi/|\beta|^2$. Hence the overall input-output map for the repeater-loss sequence is given by $\Gamma_{\pi/|\beta|^2,-i\beta}$. The fact that this map depends only on the input signal level β does not mean that one can recover a given signal after any arbitrarily-high loss. If the input signal level is reduced too much, i.e., if $\beta \equiv \eta^{1/2}\gamma \to 0$ for a fixed peak amplitude γ, then the dephasing effect at the repeater would increasingly degrade the carrier coherence, leading to enhanced fluctuations $\Delta^2 = \pi^2/(4\eta|\gamma|^2)$ for $\eta \to 0$.

We now evaluate the transmitted BER for on-off keying and direct photodetection at the end of N optical regenerators distributed along the lossy line. The input is in the coherent state $|\beta\rangle$ and all repeaters are set at their optimal working point with the Kerr coupling $\chi = \pi/|\beta|^2$, and with the nth repeater having a LL intensity given by $|\alpha_n|^2 = |\beta|^2/\eta_n$, where $1-\eta_n$ is the loss between the nth and the $(n+1)$th repeater. In this scheme, since there is no spontaneous emission from the repeater, the detection threshold should be set at one photon, and the BER is just the vacuum component of the output state after iterating the map $\Gamma_{\pi/|\beta|^2,-i\beta}$ in Eq. (1) N times on the input state $|\beta\rangle$. A numerical calculation shows that after a sudden dephasing at the first step, the state remains quite stable with a slow dephasing in the following steps. A log-log plot of the BER B versus N is reported in Fig. 4 for different magnitudes of the input amplitude β. The BER increases fast for the first ten-twenty steps. Then, there is a transition to a very stable linear regime $B = C(\beta)N$, with $C(\beta) = 10^{-0.44\pm0.02-(0.0356\pm0.0001)|\beta|^2}$. So, for example, after $N = 10^2$ optical repeaters and for input amplitude $\beta = 20$ the BER is $B = 2\times10^{-13}$. This result should be compared with the BER achieved on a lossy line with ideal photon-number amplifiers [24], where for a gain $g = \eta^{-1} = 2$ the BER is $B = 3.4\times10^{-7}$. The performance is much worse when using linear phase-insensitive amplifiers due to the spontaneous-emission noise.

In conclusion we analyzed a nonlinear Sagnac interferometer with cross-phase modulation, which is used as a repeater for on-off modulation and direct detection in a lossy line with N

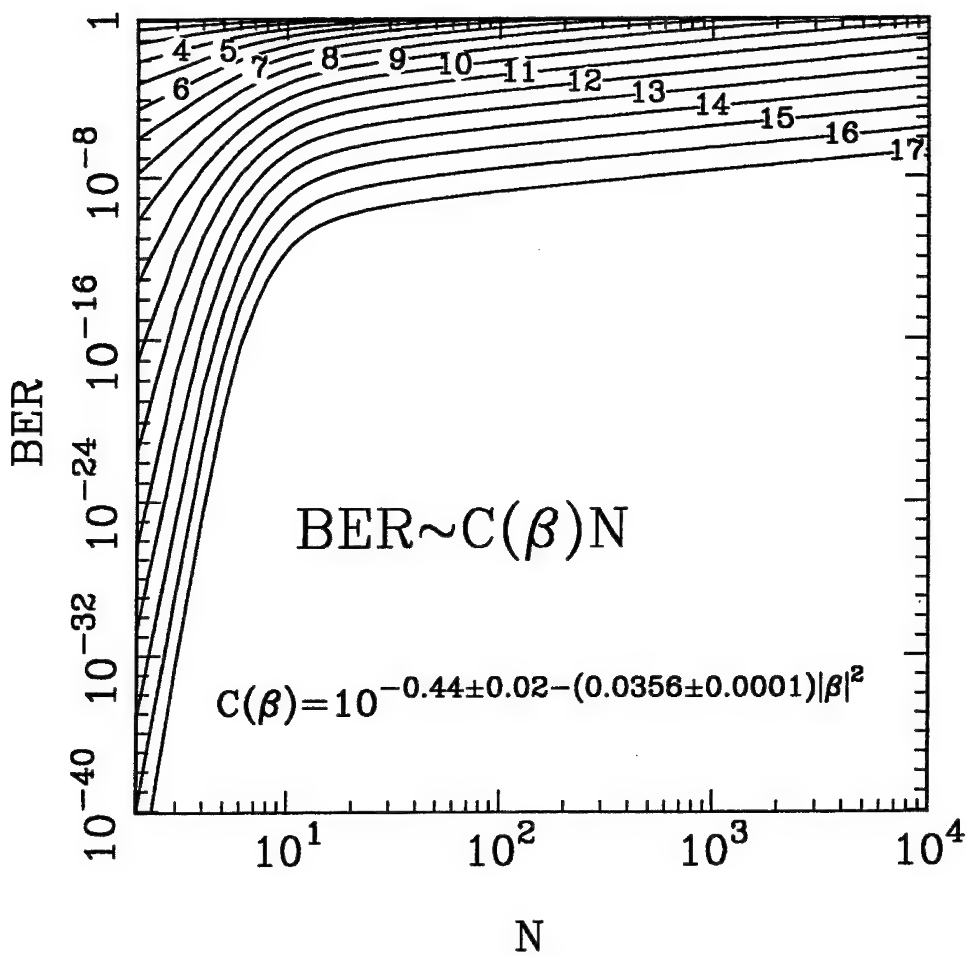


Figure 4: Bit-error rate B for a lossy line with N optical repeaters versus the number N of repeaters. Different curves refer to different input field amplitudes β, ranging in unit steps from the bottom curve that corresponds to $\beta = 17$. The slowly increasing regime for large N is linear, and its form is reported in the figure inset.

distributed repeaters. We showed that with all repeaters set at their optimal working point, the BER increases linearly with N for large N, and the proportionality constant exponentially decreases with the input signal intensity, resulting in almost error-free communication even at very low power levels. Finally, our monochromatic analysis remains valid even for short pulses as long as dispersion effects are negligible and the cross-Kerr susceptibility can be considered approximately constant over the pulses' frequency bandwidth.

2.2 Experiment to Measure the Quantum-Noise Properties of a Nonlinear-Fiber Sagnac Interferometer

Recently, bright sub-Poissonian pulses of light were obtained from an unbalanced nonlinear Sagnac interferometer [12]. The noise reduction was shown to be mainly due to the strong correlation between the pulse's photon number and phase, that develops during propagation in the Kerr medium [13]. The success of these experiments critically depends on the use of ultrashort (femtosecond) soliton-like pulses in order to achieve substantial nonlinear phase shifts in short (few meters) lengths of fiber. For picosecond pulses, however, the required longer fiber lengths lead to accumulation of excess noise that is due to scattering on thermally-excited acoustic modes of glass fiber, also known as guided-acoustic-wave Brillouin scattering (GAWBS) [14], which makes observation of quantum effects very difficult. Two schemes were developed in order to achieve broadband suppression of the GAWBS noise in squeezed-vacuum generation experiments that employed a balanced Sagnac interferometer: i) cooling the fiber to liquid-nitrogen temperatures [15] and ii) generating two squeezed-vacuum pulses, separated by a short time delay, and detecting them with a relative phase shift of π by a two-pulse local oscillator [16]. The second method, in order to achieve excess-noise cancellation, used time delays shorter than the inverse bandwidth of GAWBS, which required a GHz electro-optic modulator for fast phase switching.

In this paper we experimentally demonstrate bright sub-Poissonian light generation with a balanced nonlinear Sagnac interferometer. In contrast to the previous work, where such a device was used for quadrature squeezing of the input vacuum [15, 16], we inject a coherent-state input signal, which can be either amplified or deamplified depending on its phase relative to that of the pump, transforming a balanced Sagnac interferometer into a phase-sensitive amplifier (PSA) [17]. In the case of deamplification, the output signal can be shown

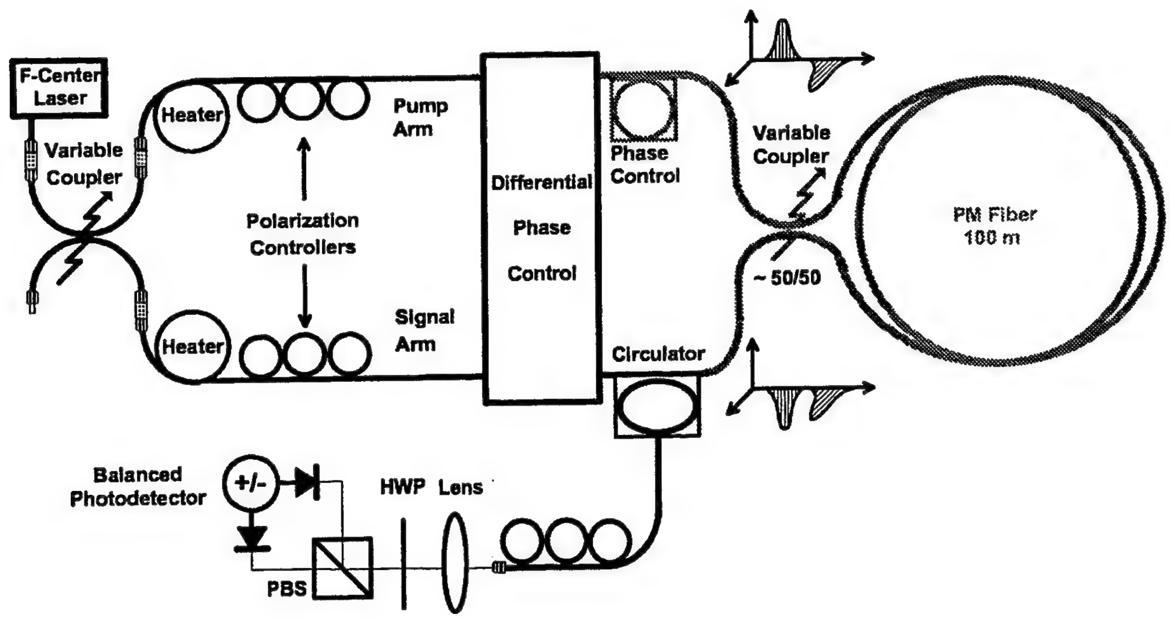


Figure 5: Experimental setup (gray line indicates PM fiber).

to be sub-Poissonian, even when the signal power is comparable in magnitude to that of the pump, which makes the quantum noise reduction robust with respect to the pump leakage into the signal arm [18]. To cancel the GAWBS noise we employ a novel technique using two orthogonally polarized pulses in both the pump and the signal arms of the interferometer. This scheme has the practical advantage of not relying on ultrafast electronics to implement phase switching and synchronization.

The experimental setup is shown in Fig. 5. A 100-MHz train of 7.3 ps sech pulses from a mode-locked KCL color-center laser, operated at a center wavelength of 1.55 μm, is divided between the signal and the pump arms. Our Sagnac loop is made with 100 meters of the Fujikura polarization-maintaining (PM) fiber. Polarization controllers in each arm are set to equally excite both axes of the PM fiber. A differential phase controller is adjusted to make the relative phase between the two polarizations in the signal arm differ from that in the pump arm by π. The optical paths of the input signal and pump are matched for both polarizations. This insures that, while the two signal polarizations arrive at slightly different times at the input of the Sagnac interferometer, they are independently deamplified, with the same gain, by the corresponding polarizations in the pump arm. The output signal, separated from the input by a circulator, is directed onto a balanced photodetector, where the resultant photocurrent noise is measured. Because of the relative π phase shift, the GAWBS noise

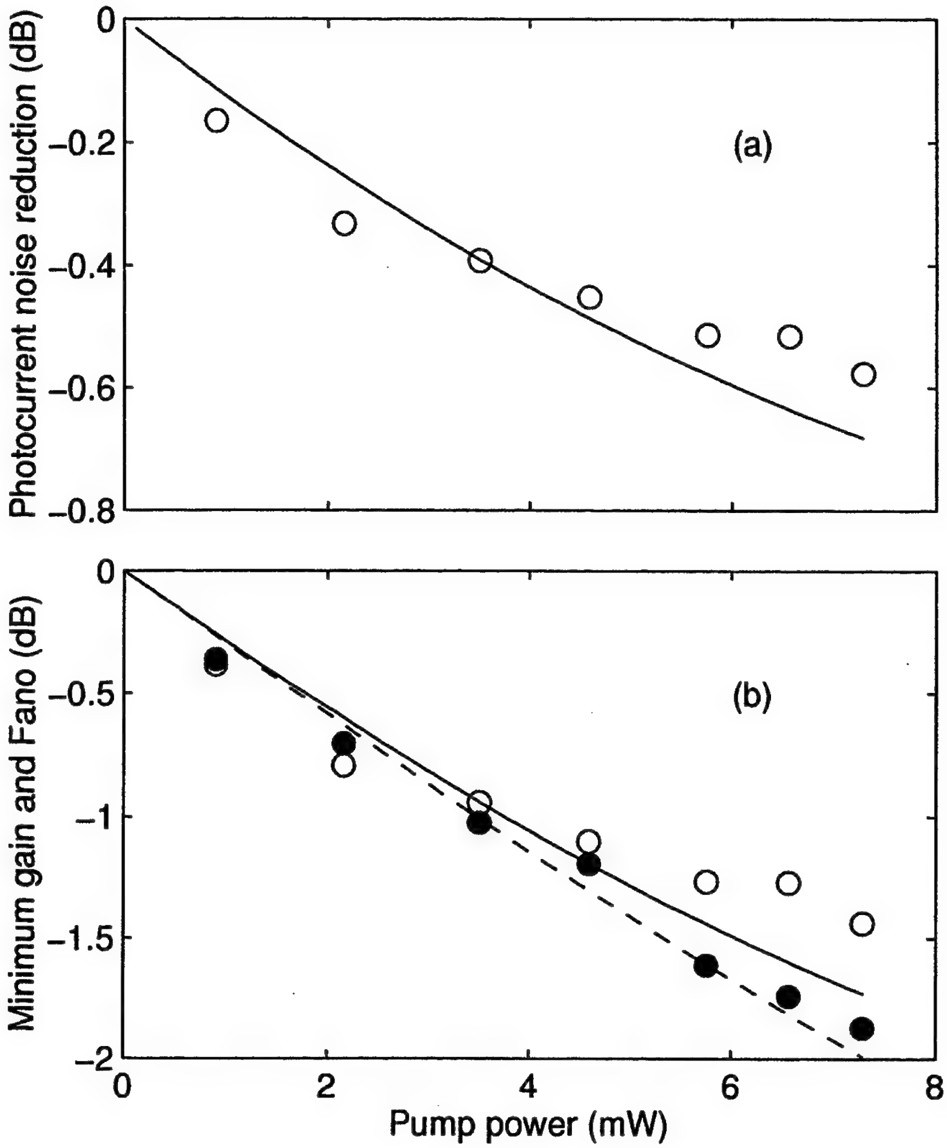


Figure 6: (a) Photocurrent noise normalized to the shot-noise level (circles – experimental data, solid line – theory). (b) Fano factor of the output light (circles – experimental data corrected for $\eta = 0.44$, solid line – theory) along with the PSA power gain (filled circles – experimental data, dashed line – theory).

due to the cylindrically-symmetric acoustic modes is anticorrelated in the two output signal polarizations. Our detector integrates over the two polarization pulses, which are separated in time by 170 ps due to the birefringence of the PM fiber, thus canceling the GAWBS noise caused by these modes. Although the excess noise due to torsional-radial depolarizing modes is not canceled by this scheme, their contribution was shown to be relatively weak [19].

In Fig. 6a we plot the resultant values of the power spectral density of the sum photocurrent, normalized by the corresponding values of the difference photocurrent, the latter representing the shot noise level. The phase difference between the signal and pump arms was adjusted to obtain the minimum relative noise factors, as the amount of power in the pump arm was varied. The noise measurements were done at a frequency of 60 MHz with 1 MHz resolution bandwidth. We have observed a maximum noise reduction of –0.6 dB below the standard quantum limit. The overall detection efficiency in our setup is $\eta \approx 0.44$. The Fano factors of the deamplified light, inferred from the photocurrent noise by correcting for $\eta \neq 1$, are plotted in Fig. 6b along with the corresponding minimum values of the PSA power gain. The minimum Fano factor thus inferred is –1.4 dB.

The predictions of a quasi-cw linearized quantum theory of a Sagnac-loop PSA [18] are also shown in Fig. 6, and are found to be in good agreement with the experimental data. The observed sub-Poissonian behavior, which could not be seen in the absence of a second π-shifted orthogonally polarized pulse, indicates that our GAWBS cancellation scheme is a viable and practical technique for achieving squeezing in fibers.

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